N71-31081

NASA TECHNICAL TRANSLATION NASA TT F-13,816

PROBLEMS ASSOCIATED WITH THE GRAPHIC INTERACTION OF OPERATOR-COMPUTER

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Translation of "Problemi connessi con l'interazione grafica operatore-calcolatore," Milan, Centro Informazioni Studi Esperienze, Report CISE -115, March 1968, 24 pages

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 NOVEMBER 1970

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INTRODUCTION

The purpose of this paper[(1)] is to discuss the principal problems confronted in the heart of the program COLD for the realization and the experimentation of a graphic system of man-computer communication. I must admit, above all, that my statements are not the result solely of my activity, but are also the result of the work of a group of researchers and technicians that work with me, and of collaboration with the Institute of Electrical Technology and Electronics of the Politechnic Institute of Milan, with the Calculation Center of the Faculty of Engineering of Bologna, and with the individuals responsible for the project CONCOMP of the University of Michigan at Ann Arbor. Of the most active collaborators I must mention: engineers I. Alleva, R. Galimberti, R. Laschi, G. Valle; doctors A. Ghirardi and G. Sclocchi; S. Fortunati and G. Moretti. I must also thank professor E. Gatti for innumerous suggestions and continual assistance. /1*

Digital computers have for some time been used in engineering and in practically all scientific fields. Only recently, however, has their use as co-helpers in man's creative process been the object of study. Experimental attempts made with graphic communication techniques have obtained and are now obtaining a high level of efficiency in man-computer interaction, exploiting to the fullest man's intrinsic characteristics and those of the machine.

The creative process of the human mind, at least in the scientific field, is understood above all as a process of inventive learning. This

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* Numbers in the margin indicate the pagination in the original foreign text.

(1) "Invited paper" presented to the Congress of the S. I. F., Bologna, October, 1967.

consists, in general, of the search for a trial solution and for the methods of arriving at the solutions. It is then a search for the verification of these methods and the solutions, to ascertain that all the data have been satisfied, and that the desired results have been achieved. This verification suggests the possible alteration of the outlined solutions.

This iterative method of researching the solutions and the methods of /2
arriving at solutions is in general a process largely undefined. Detailed algorithms that describe it do not exist, as a universal algorithm to construct algorithms for problem solutions does not exist. This does not mean to say that certain processes now considered peculiar to the human mind cannot in the future be formalized and therefore mechanized, but simply that now there is an infinitely extended hierarchy of intellectual processes that are now beyond the frontier of those which are easily and economically formalizable — no matter how we succeed in extending this frontier.

It is exactly between the informalizable mental processes and those describable with an efficient algorithm that we place the study and experimentation of an effectual union of man and computer — a union that brings out the best of the human mental capacity of assimilating information and rapidly formulating a decision, and the ability of the digital computer to resolve with precision and rapidity problems in which many similar operations are repeated. Man's capacity for synthesis and decision-making in fact complements the enormous efficiency, and power of memory and calculation of the digital computer.

The optimum means of man-computer interaction must permit a homogeneous blending of the capacities of the man and the machine with a rapid response time, to the overall goal of improving man's learning and memorization of the significant results and therefore of his decision-making capacity. It must permit interaction in real time. Interaction in real time means an interaction in which the computer response to an operator request is furnished in a time adequate for the operator's own capacity of assimilation — that is, neither too fast nor too slow if the principal goal of the means of interaction is to take advantage of the best of man's capacities, and to permit him to exploit the great calculating capacities of the computer with the techniques of time-sharing. /3

It is common knowledge that the language of highest efficiency for scientific communication between men is graphic language. In fact, man often perceives the solutions to his problems in graphic form. Moreover, it is well known how necessary and efficient the use of a sketch is, which functions as a temporary memory in the creative process of the human mind. Current technology still does not permit efficient means of communication for three-dimensional figures that are so near in the world surrounding us. Instead, means are available for a graphic alphabet of two-dimensional symbols, often having a conventional meaning tied to the particular use of the language itself. Two-dimensional means of graphic communication, eventually augmented by the use of color, are therefore the most adequate means of man-computer interaction for the majority of needs.

Given the large practical and speculative interest in these new techniques of man-computer interaction, we have undertaken a vast research program with the double goal of better characterizing the peculiarities of graphic means of communication, and of experimenting with some applications in which the advantages of an efficient in line interaction between the operator and the machine may be more evident.

In the following, I will first briefly describe the system upon which /4
the experiments were performed. Then I will present all the portion of the programming developed by us to render the operator-computer graphic communication possible, and finally I will discuss quickly some of the applications completed to date, omitting those which still have not been sufficiently tested.

2. SYSTEM OF PROJECT COLD

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The system consists of an IBM 1800 computer with 16 thousand memory positions of 16 bits each, and a memory cycle of 2 microseconds. It is equipped with the following units: a console typewriter, three disk storage units mounted on independent communication channels to the computer, a printer, a card read punch, one numerical input unit, one analog input unit, a numerical output unit, and one output unit for "interrupt" signals.

The graphic display unit is an I. D. I., model CM 10114, consisting of a special tube with slow magnetic and fast electrostatic deflection, service and interface circuits, two storage registers, a small control unit which permits the execution of simple instructions (plots of points, of series of points, of characters, and of continuous and broken lines; control of several levels of screen image intensity, and possible low frequency modulation of this same intensity). Typical trace time for a point is approximately 15 microseconds, and for a line of any length about 50 microseconds. Graphic information is introduced using a light pen connected to the computer "interrupt" channel. For all functional details of a graphic display system and light pen, refer to the comprehensive bibliography reported in References [1] and [2].

The system has some serious limitations, namely: the fast memory capacity is somewhat small, given the large overhead requirements of the service programming; and the channel to which the graphic display unit is attached is unidirectional. The graphic system uses part of the computer's fast memory as a storage buffer for the sequence of graphic instructions (exit list). This part of the memory is accessible both to the computer control unit and to the graphic system control unit, which is accessed

in a "cycle stealing mode".[2] The unidirectionality of the channel to which /6
the graphic system is attached requires that for any graphic operation made with the light pen, however simple, control is regained using the "interrupt" function of the central computer unit over the buffer storage of the graphic unit. Moreover, it impedes the graphic system control unit in its execution of simple branching instructions which would permit exit lists organized below in the program, with great savings of memory above all in the complex figures composed of many equal elements. The small capacity of the fast memory actually available ($\sim$ 8000 words of 16 bits) compels the frequent use of the disk units with a great loss of time. As a result, it is often difficult to obtain an effective functioning in real time of the operator-computer interaction, above all in those problems where the computer is called upon to execute many computations, and the man to formulate a rapid choice based on results presented in graphic form. Figure 1 shows the external view of the system of project COLD.

3. SERVICE PROGRAMMING /7

For efficient functioning, the graphic system requires considerable service programming support. Given the particular configuration of our system and the limited capacity of the available fast memory, we were not able to utilize existing programs on the market, the majority of which are incomplete and not optimized. On the other hand, the optimization of the system has required careful programming of the elementary operations, necessarily dependent on the characteristics of the system itself.

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(2) This is a type of common functioning of many modern computers in which numerical data can be introduced or taken from the computer memory without interfering with the central control unit of the computer itself, but utilizing external registers and "stealing a memory cycle" for every word transferred under control of a synchronized signal generated by external equipment.

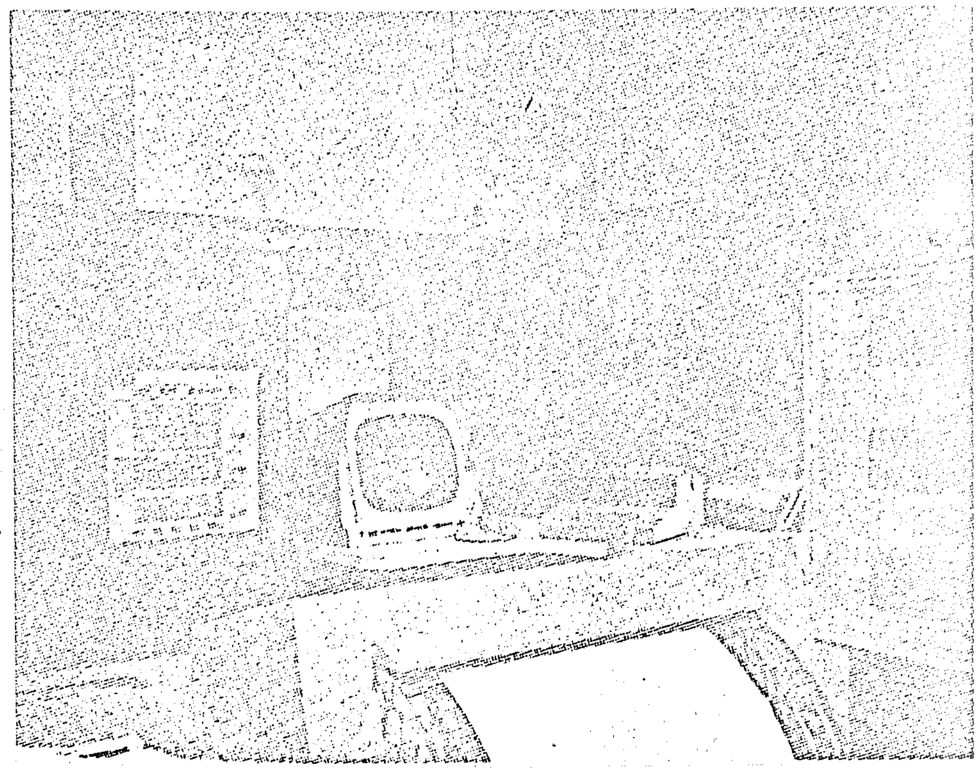

Figure 1. View of the system of project COLD.

Programs studied and produced were programs for light pen use ("tracking" and "picking"); programs for the construction and control of the instruction set and data for the graphic unit; programs relative to the linear transformations of the image (scale factor, translation, rotation, parallel projection, perspective); and programs for the graphic presentation of calculation results.

The entry of graphic information can be done in two ways: with the functioning of "tracking" and with that of "picking". In the following I will outline briefly the "tracking" program. In the "tracking" function the coordinates of points on the screen are entered into the computer memory, the meaning and value of which are tied to the program which has the input data. The resolution with which the coordinates of points can be indicated

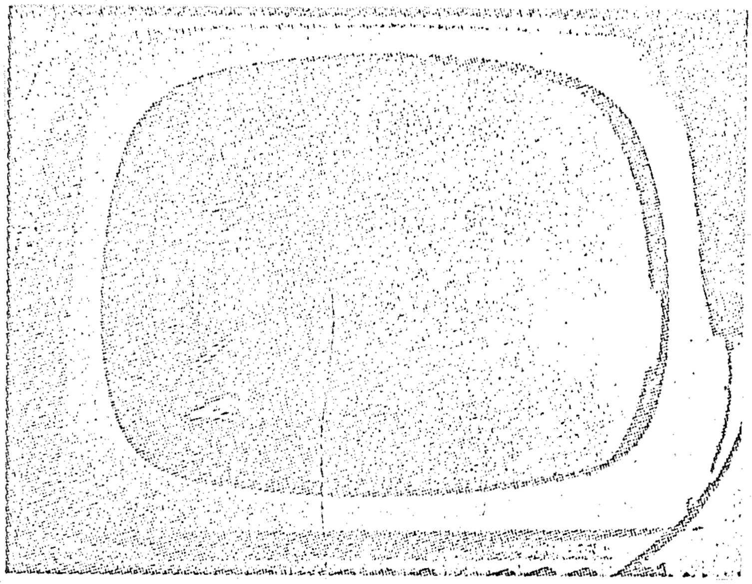

Figure 2a. Series of graphic instructions that permit the choice of "tracking".

is normally on the order of 1%.(3) The coordinates to be entered are specified on the graphic system screen with a figure subordinate to the position of the light pen.(4)

Figure 2 illustrates the diverse modalities of the functioning of "tracking": 1) continuous registration of the successive positions of the subordinated figure; 2) registration of only some of these positions, chosen with simple metric laws (for example, when the distance between two successive positions may be greater than a prefixed value) that effect a simple mask over the traced figure, relating the noise components to high frequency; 3) tracing of vectors: the vector beginning with a point previously entered has as its terminal point the subordinated figure and follows it until this figure is not seen by the light pen for a prefixed time (on the order of a second). When such a time has passed, the vector is completed and the con- /8

(3) We have finally produced a method of entry which, taking advantage of a vernier technique, permits an easy resolution of one ten thousandth.

(4) The velocity with which the subordinated figure follows the light pen depends upon its form and upon the program which controls its movement. A method of automatic anticipation of the direction of movement has been studied, which has given interesting results, yet does not require complex and cumbersome programming: this permits a high velocity of writing with the light pen, and it is almost impossible to lose the subordinated figure.

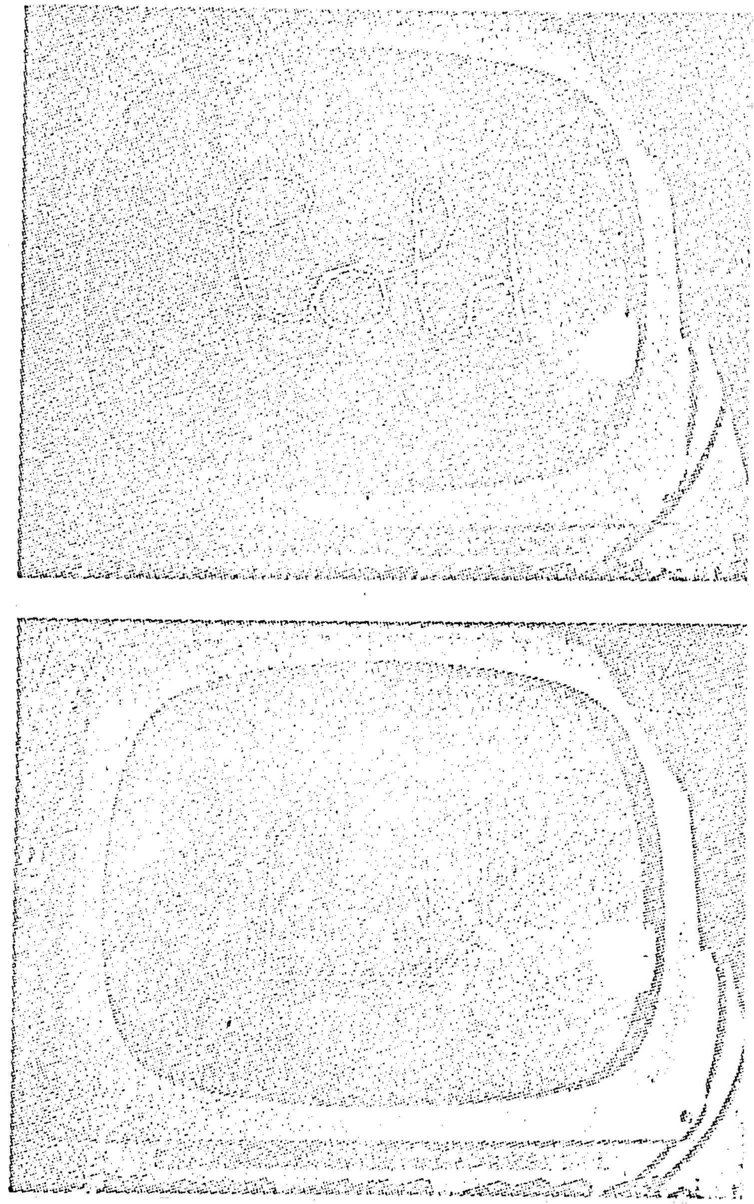

Figure 2b. Figure traced on the screen with the light pen, with type 2. "tracking" (see text)

struction of a new vector is begun; 4) tracing of vectors with pre-established direction: the projection of the subordinated figure according to the direction of one of the cartesian axes on the line of the data direction, passing the initial point of the vector, and utilized as in 3); 5) entry of an isolated point.

Obviously the designed figure is presented on the screen even during its own tracing; this presentation is interrupted only during the presenta- /9 tion of the subordinated figure. The temporal separation of the two representations renders the system sensible only to the luminous signals of the subordinated figure, and therefore permits passing over the traced figure with the light pen during the operation of "tracking" without any disturbance.

4. RESEARCH COMPLETED /10

Of the projects completed with the graphic system described above, I am presenting only those that have been the object of sufficient experimentation.

A. The planning and the detailed description of definite objects with double curved surfaces represent an important and interesting application of man-computer graphic communication. In industry the problem is manifested above all in the planning of the ships' hulls, of fuselages, wings, and ailerons of aircraft, of automobile bodies, of the blades of a propeller or turbine, of an optical lens, of a curved or arched dam, of surfaces of architectural interest, etc. In collaboration with the Institute of Electronics and Electrical Technology of the Politechnic Institute of Milan, we have produced [1, 2] a group of programs for the generation and the manipulation of double curved surfaces that have proved to be efficient enough and have aroused the interest of industry.

Among the many problems confronted, I remember that of the data structure, which was, in general, the most important in all of the graphic communication systems' applications. In this particular case, given the simplicity of the topological relations between the data and the elaborations requested, the most convenient structure of the data resulted from a simple compromise between table and list structures.

B. An efficient operator-computer interaction, in the spirit of the goals indicated in the introduction, should permit the operator to express himself graphically, just as he is used to doing with pencil and paper. It is often easier and economically more convenient to program a computer to interpret a sketch, than to instruct a large number of users in a new expressive language.

To give the user this possibility, we have undertaken, in collaboration /11
with the Computer Center of the Faculty of Engineering of Bologna, the study of a program which renders the computer capable of interpreting all the alphanumeric characters, and an ensemble of electrical symbols hand-traced by the operator on the screen. The problem of recognition associated with this application is simplified notably by the following facts: besides the coordinates of points that compose a traced figure, the temporal sequence in which the points are entered is memorized (this is supplementary information of a particular utility, given the notable grade of uniformity in the manner of writing found in the many subjects taken in exams). An elevated grade of recognition is not necessary (it is sufficient to recognize 90 - 95% of the designed symbols, since — being the line operator — he can redesign the symbol if the computer has not interpreted it correctly). On the other hand, the program that performs the recognition requires a functioning in real time, (anyway, to save time, even during the tracing of the symbol), a rapid recognition, and a limited occupation of memory space.

The problem was resolved in the LAMA program [3, 4] that has given sufficient results. Its use, associated with other programs — for example, circuit analysis — is currently in the experimental phase.

C. Analysis of electronic circuits [5]. The graphic means of communication is much more convenient and natural for specifing a circuit than is punching a pack of cards or a tape. This is much closer to how a draftsman traditionally works and also it permits a rapid and less tiring operation. This allows the use of the computer for circuit analysis even to a user completely untrained in programming, without having to write equations nor prepare data and punch cards. All topological and quantitative information relative to a network are given graphically, and all the results are also presented graphically: a simple network is therefore possible in which the operator, who is an expert draftsman, simply specifies the network and examines its behavior as he would, for example, with an oscilloscope, studying the effects of the variation of the parameter values, components not yet found on the market, or functional errors and conditions which would lead to the distruction of the simulated circuit. /12

The program produced, in use currently, is subdivided as follows: graphic entry of the network, its value, choice of the type of analysis (frequency response of the network, transitory response), analysis, presentation of results, possible alteration of the topology and of the parameter values. Figure 3 presents some images of the diverse phases of the program.

For all program details and for the methods of analysis chosen, refer to Reference [5].

D. Resolution of partial differential equations [16]. We are confronted with the problem of elliptical differential equations, the study of electrostatic fields, magnetic fields, thermal fields, etc. We noted the difficulties of plotting the profile and the boundary conditions to obtain the desired course of the field. We furnish data to the computer to resolve a Dirichlet problem by designing a boundary on the graphic unit screen, always specifying graphically the boundary conditions. The computer resolves the differential equations of the field, and graphically presents the results across the lines of flux or the equipotential lines (plane fields).

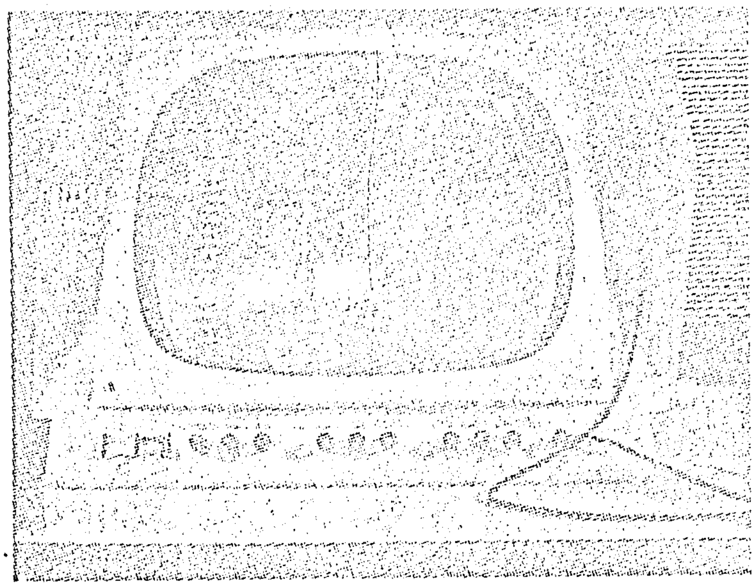

Figure 3a. In the upper left we see the three instructions for connect, end entry, and cancellation. Then, towards the bottom, the electrical symbols used for graphically entering a circuit. In the center there is a circuit with a voltage generator, resistances, condensers, and inductors. Note the distinct geometric masses.

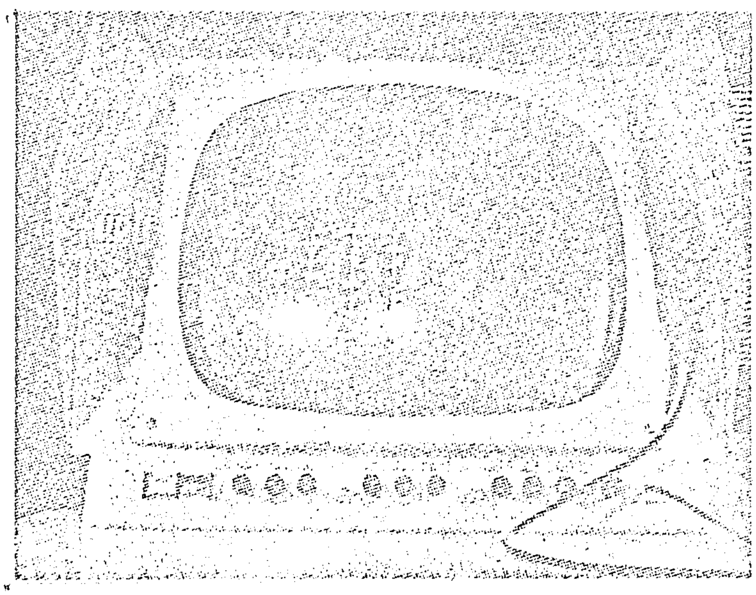

Figure 3b. The same circuit as in (a), after the computer has constructed the equivalent graph. The letters represent the names of the modes of the equivalent graph.

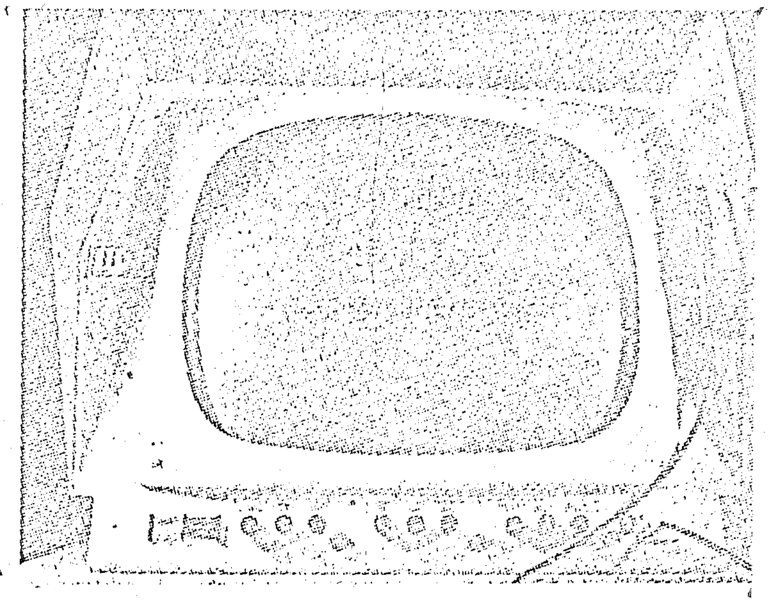

Figure 3c. After having entered and given value to the circuit, the choice of the type of analysis is made; three methods of analysis are available: transit analysis with the method of Katzenelson, transit analysis with the iterative method, and frequency analysis with the state variables method.

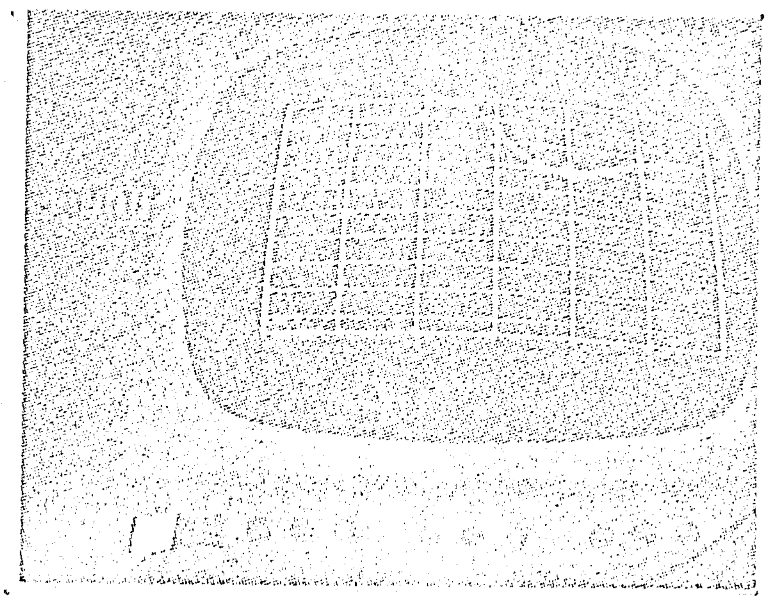

Figure 3d. Trace of a wave form of the voltage difference across the ends of resistor EA (see Figure 3b).

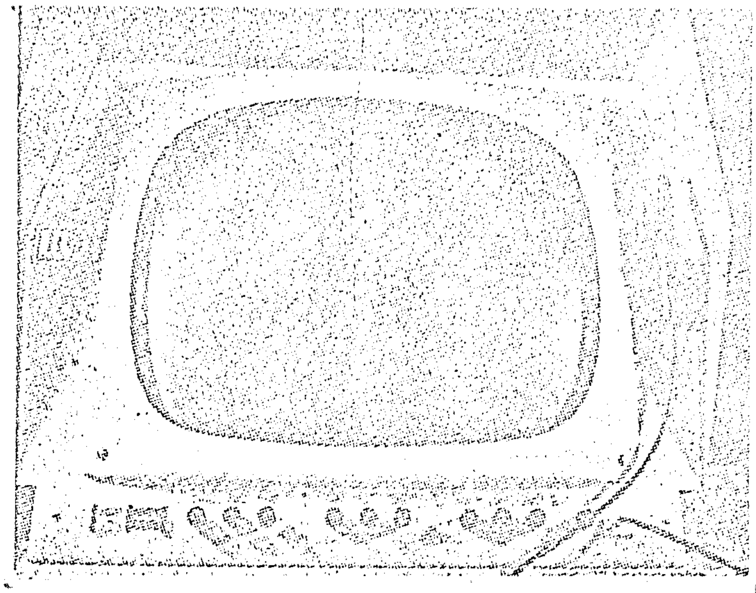

Figure 3e. Circuit with a saturated inductor (bipolar CD) and a non-linear resistor (bipole DA).

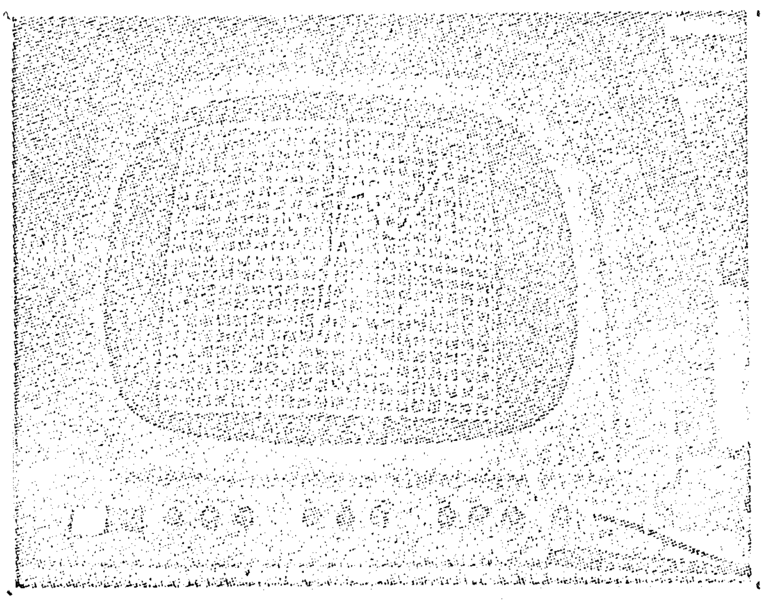

Figure 3f. Characteristic EV of the bipole DA.

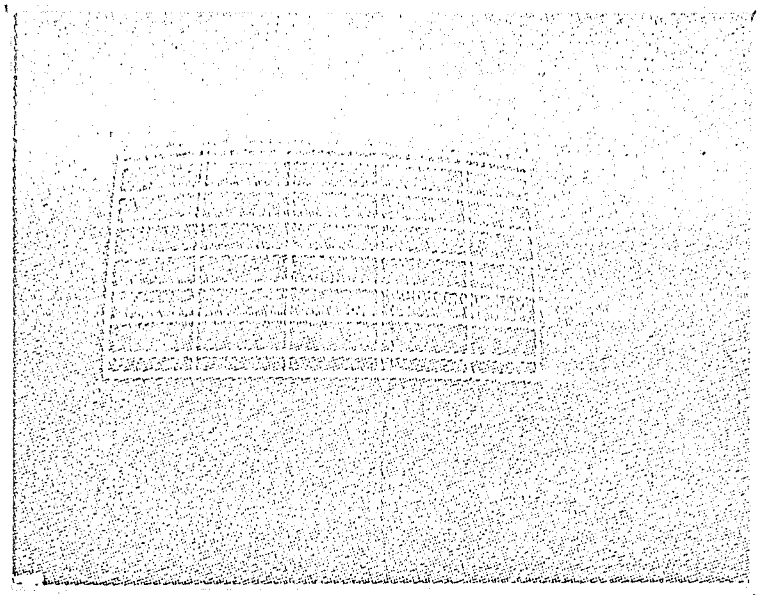

Figure 3g. Trace of a wave form of the current through the saturated inductance.

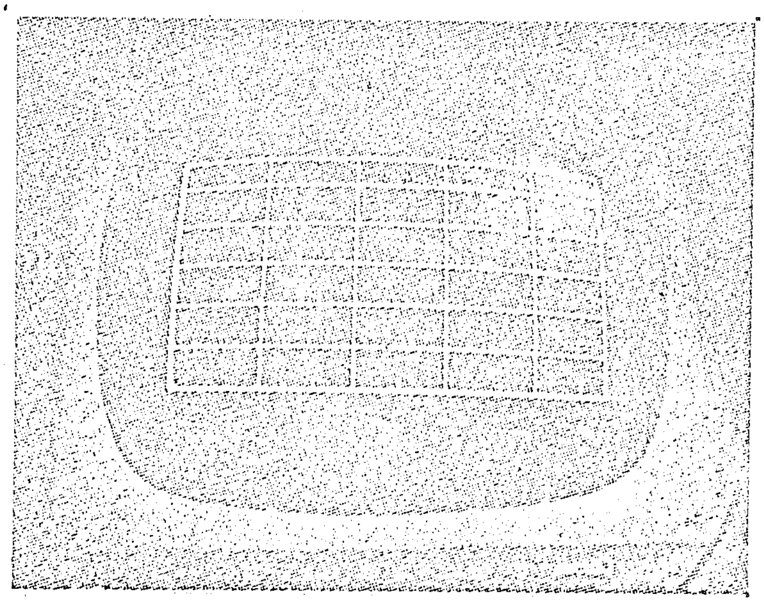

Figure 3h. Trace of a wave form of the voltage across the ends of a non-linear resistor DA.

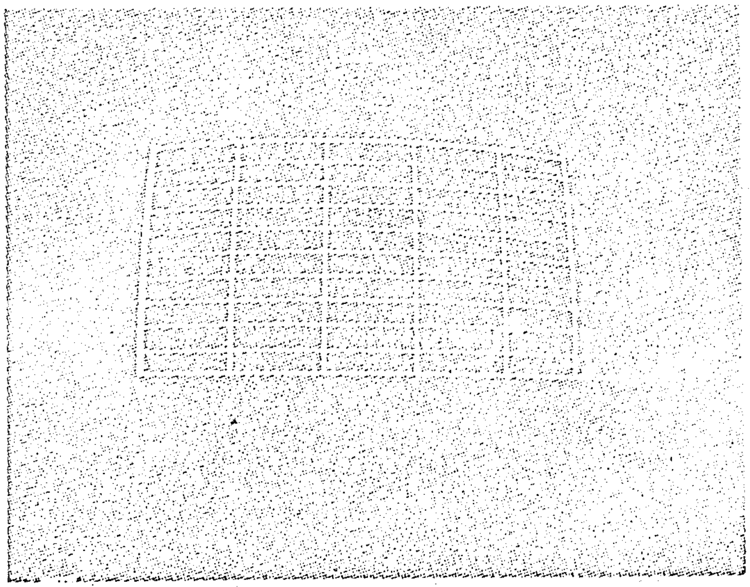

Figure 3i. Current through the same DA resistor.

The problems confronted in C. and D. are two types of examples of iterative plotting, where the choice of the data alteration entered is left to the operator, guided by his intuition and experience, with the end in mind of achieving the desired results.

5. RESEARCH IN PROGRESS

A. Internal structure of /14 the data: This is a problem of major importance that has already been confronted in the programs mentioned in paragraphs A., C., and D. of the prededing chapter. The solutions adopted there are rather particular solutions, strictly connected to the type of operations that are performed on those data. The adoption of a data structure of general validity may be impossible or at least inconvenient under many aspects. The analysis of the peculiarities of problems that condition the data structure is particularly interesting. We are referring to the planning of several types of structures of general enough validity and their experimentation to prove the efficiency and the flexibility of them, also considering the occupation of memory and the execution times of the most frequent operations.

B. Simulation of an analog computer. There are already available programs that permit the simulation of an analog computer on a digital computer, with several particularly interesting advantages. The use of the graphic system for beginning a problem, for example, using the common symbology of the block diagrams for the analog computer, and for presenting the results, permits the use of the digital computer as if it were an analog computer, with all the advantages mentioned above.

The problem is not much different for us than that already resolved for the introduction of an electrical network and for the presentation of results.

C. Iterative analysis and synthesis of block diagrams for linear systems. The advantages of a digital computer linked to a graphic unit in the analysis and synthesis of subordinated systems is obvious. Singular blocks, if linear or can be made linear, can be represented on the graphic unit by their transfer function, represented analytically or by an experimental graph. The topology of the system can be simply designed with conventional symbols on the graphic unit. The results, for example, the diagrams of Bode and Nyquist, are presented graphically guiding the draftsman in the selection of the correct networks and eventually in the changing of the /14
topology of the system. It is observed that no limits exist in the resolution with which the data can be expressed with the graphic unit, inasmuch as the resolution of the cathode ray tube can be extended as much as desired using a scale factor.

D. Operator-computer interaction during the acquisition and processing of data from physics experiments. Abundant literature exists on the subject, but the possibilities offered in this field by means of graphic communication are still not completely known.

E. Associative memories: in these memories, the search for a memory cell is not only tied to the contents of the cell itself, but also to its relations with the contents of other cells. This organization of the memory, beyond the great interest which it presents when one must manipulate in much interrelated data in a complicated way, is particularly fascinating for its similarity to the way in which the human mind seems to be organized. It is not addressable based on the position of the memory cell, but rather based on its contents and on the associations with the contents of other cells. Considerable work performed by us in this field is in process of completion and we hope to be able to furnish a documented and significant analysis of the peculiarities of these memories before long.

F. Applications of graphic communication systems to the problems of architecture: the architect has always looked upon the digital computer as an instrument which limits his creative liberty, and moreover, with extreme /16
diffidence. Given however, that the architectural profession requires a decisional capacity which is practiced after an accurate examination of a large quantity of data and relationships, which the human mind can accomplish and remember only with difficulty, the joining of a computer to architecture appears, if not necessary, at least hoped for and without doubt possible. Our work in this field, now limited to simple urban problems is now beginning to yield significant results. It is proceeding slowly because of language difficulties.

6. CONCLUSIONS /17

I could continue at length enumerating problems that we have begun to study, or that it is our intention to tackle before long. Their number grows larger with our increased familiarity with the graphic system of communication. I believe, however, that it is useful to summarize briefly the results obtained to date which have sufficient generality.

Foremost, it is evident that an operator-computer interaction in the search for a problem solution is useful only when an algorithm for reaching the solution using the computer alone either does not exist or is not economical, whenever rapid intervention of the operator's judgment is necessary. Under these conditions, the use of the graphic unit is seen even as a simple way out. It is obviously a convenience to see the results of a long calculation graphically on the tube's screen, but if this does not serve for a subsequent operation by the operator, this convenience can be a rather costly and unjustifiable luxury.

The system with which we are experimenting has given satisfactory results for the part relative to graphic communication. The program difficulties due to the unidirectionality of the channel to which the graphic unit is attached can be overcome easily enough by rendering accessible to the outside the address register for the functioning in "cycle stealing mode", at least in reading. The programs of "tracking" and "picking" produced have revealed themselves adequate to the needs of the applications made to date. Response times of the graphic unit, the use of part of the fast memory of the computer as buffer storage utilized in "cycle stealing mode", the graphic unit-computer interaction using the "interrupt" channel, and the exit table are seemingly satisfactory. We can therefore conclude that the computer is more than sufficient for a complete service to the graphic unit. /18

Instead, where the fast memory capacity is insufficient is in the resolution of the majority of problems begun on the graphic unit (for example, the circuit analysis or the resolution of the elliptical differential equations). For these problems it is necessary to resort to a large computer, utilizing time-sharing, on which numerical problems of major dimensions can be resolved, leaving to the computer connected to the graphic unit the task of serving the graphic unit and of resolving the minor problems. The frequent use of the disks, and in general, of mass external memories has shown itself to be too inconvenient both for the calculation times and for the programming. In particular it can render an effectual real-time interaction impossible, given the long wait times that it can introduce between the operator's formulated request and the computer's response.

The programming is often non-conventional and particularly interesting. Many problems are still unresolved; others have been only recently uncovered. In particular, I remember the problems connected with the choice of the data structure, with the associative organization of the memory, and with the elaboration of the "interrupt" signals. Naturally there are all the problems associated with the condition of the computer upon which one a peculiar to a graphic system, if not for the need of a rapid response from the larger computer (high priority).

The possible applications, as I have already mentioned, increase in number more and more as familiarity with the system increases, and naturally, hand in hand with the completion of the service programs which render the system more flexible and easier to use. The applications that I have presented to you in this respect are but a few examples that we have chosen solely because they were those most adapted to our previous experience. I hope, however, that they have been sufficient to show you the principal characteristics of the graphics systems of operator-computer interaction and their potential applications.

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Translated for National Aeronautics and Space Administration under contract No. NASA-2035 by SCITRAN, P. O. Box 5456, Santa Barbara, California, 93103.